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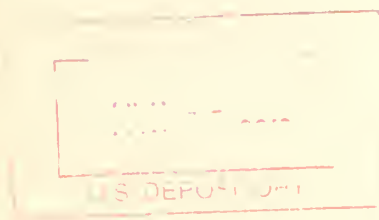
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PAPER-HONEYCOMB CORES FOR STRUCTURAL SANDWICH PANELS

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By

ROBERT J. SEIDL, Chemical Engineer

Forest Products Laboratory,³ Forest Service
U. S. Department of Agriculture

Summary

Bonding of paper-honeycomb cores between thin and strong facing sheets results in sandwich panels that are becoming increasingly important for structural applications. The panels are strong, stiff, light, and economical of raw materials. They can be made by processes that lend themselves to mass production from materials that are produced in large volume.

This paper summarizes briefly some of the research at the U. S. Forest Products Laboratory on sandwich building panels having cores made from corrugated paper of low resin content. Extensive testing of these panels in the wet and dry condition has shown that satisfactory performance could be expected, and a considerable amount of data has been obtained to aid in the structural design of panels. For use in dwelling units, strength tests have indicated that a suitable sandwich wall panel is comparable to conventional house construction in bending strength and resistance to vertical loads. With proper treatment, the cores have reasonably good decay resistance. Thermal insulation values are relatively good and depend on the core density and specific construction; for some uses, the thickness of the panel may be determined by the thermal requirements. Insulation values can be further improved by filling cells with materials such as foams or loose insulation.

Bowing of panels due to differential moisture and thermal conditions was found to be of approximately the same order as that of insulated, stressed-facing panels made of plywood glued to wood frames. The fire resistance of

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honeycomb panels is appreciably higher than nearly hollow panels with like facings. Filling of cells with foamed resin further increases fire resistance. Results of accelerated aging tests are favorable. Durability and bowing under outdoor conditions are under study in a sandwich-panel test unit, which was built in 1947 and is still in very good condition.

Introduction

The principle of the sandwich panel was undoubtedly put to effective use for many years before it was defined by engineers and recognized as a separate type of construction dominated by certain mathematical principles. General recognition occurred during the accelerated search for high-strength, lightweight materials for aircraft in World War II. Simply stated, a sandwich panel consists of an appreciably thick core of a low-density material bonded on each side to a thin sheet of strong, stiff material. A great variety of facing materials, such as wood, hardboard, asbestos board, aluminum, and plastic laminates, have been bonded to many lightweight core materials such as balsa wood, rubber, plastic foams, and formed sheets of cloth, metal, or paper.

The new and ingenious materials, constructions, and ideas for use multiplied rapidly. Stringent demands for strength and special characteristics were set by designers to meet needs for wartime aircraft. As the development progressed, a distinction between highly specialized aircraft panels and other general building panels became evident. Obviously, a radical change in the outlook regarding materials, properties, and economics was indicated, although the principle remained unchanged. Demands for strength appeared less exacting and requirements for durability and thermal insulation were perhaps more critical for building panels than for aircraft panels. Problems of supply and cost were paramount for building panels. Cores made of sheet materials, such as cloth, nonwoven fabric, or paper formed into cellular configurations of one kind or another, became more important. Then careful consideration was given to economics, availability, and other properties, it became increasingly clear that paper would play a very important part in the large-scale development of honeycomb. It may indeed be only a slight overstatement to say that paper is almost the only material apparent at present for the large-scale development of high-strength honeycomb panels.

In 1947, following several years of research with lightweight, paper-core constructions and sandwich panels at the Forest Products Laboratory, the status of the work was reviewed from the standpoint of panel applications in building. Many of the most promising ideas were gathered together and crystallized in the form of a sandwich-panel test building unit for outdoor exposure (11).¹

¹Underlined numbers in parentheses refer to literature cited at end of report.

Since the erection of the test unit, a continuing interest in the structural sandwich panel has developed, as indicated by the large number of inquiries received from an unusual variety of sources. Many are interested in only certain phases of the development, such as fabrication of the core or pressing of the panels. Pulp and paper mills endeavoring to increase the number of products possible from their raw material consider the sandwich panel as an additional long-term outlet for paper. Some resin manufacturers consider that manufacture of sandwich panels provides a promising use for their products in core treatment and in plastic sandwich facings. A few boxboard mills have observed the similarity between their regular products and the honeycomb and are following the development closely, thinking perhaps of the application of boxboard experience to honeycomb and, conversely, honeycomb principles to boxboards and containers.

Plywood and veneer mills are interested in sandwich panels as a means of increasing the monetary yield from a given supply of logs. Metal companies ask about the feasibility of using metal as facing material and see in the sandwich panel an opportunity to use thin metal sheets for applications where they previously were not suitable. The advantages of sandwich construction in furniture and doors are evident to makers of these products. Architects and builders interested in new building materials inquire about strength, fire resistance, and thermal insulation afforded by the honeycomb core, feasibility of using sandwich construction in buildings, and possible sources of sandwich panels.

Makers of hardboards and composition boards visualize new and interesting uses for their products. The continuous support that they provide makes fiberboards themselves suitable for items such as walls, partitions, and doors. When fiberboards are used as facings, the possibility of making high-strength structural panels from pulpwood and woods residues is evident.

Basically, the problem of making honeycomb from paper can be viewed as one of "blowing-up" a certain volume of a dense paper to yield a much larger volume of a low-density cellular structure with certain properties. After the spacing between sandwich facings has been determined by design, the honeycomb must fill all of the volume between the facings. Density of core is therefore one of the key factors in economy, as the materials are relatively costly on a weight basis, and they must be made to provide the greatest possible volume consistent with adequate properties.

Paper can be "increased in volume" to produce core in numerous ways. Three of the more prominent types used for sandwich panels might be described as "expanded," "figure 8," and "corrugated." In the expanded type, sheets of treated paper are laid up and interspaced with parallel and uniformly spaced strips of adhesive. Successive strips of adhesive are placed so that the centers of any one layer are positioned at midpoint between the strips of the preceding and the succeeding layer. The blanks after bonding are expanded to form hexagonal cell sections, as shown in figure 1. There has been an increasingly large interest in honeycomb structures of this type (1, 2, 4, 5, 7).

To produce the figure-8 core, a ribbon of paper is looped and bonded to form circular cells resembling a figure 8 in cross section, as shown in figure 2. For the production of either the figure-8 type or the expanded type, special machines are required.

To produce the corrugated type of honeycomb, the cell or flute is made by hot forming paper between fluted rolls on equipment of the type used in making corrugated container board. The corrugated sheet, with or without uncorrugated interleaving sheets, can be assembled in many ways. The three types discussed chiefly in this report are shown in figures 3, 4, and 5.

Each type of core has advantages and disadvantages peculiar to its construction. The differences lie in equipment needed for production, limitations in resins and adhesives, relative difficulty of accurate cutting, strength, thermal insulating properties, ease of shipment, and other factors. As far as the base material and resin treatment are concerned, such problems as fiber, resin, wet strength, and durability are substantially common to all types. It was therefore intended that the results of this work should apply to any honeycomb structure made from paper treated with phenolic resin, although most of the data were obtained from sandwich panels having corrugated paper cores.

This report summarizes some of the research that has been conducted at the Forest Products Laboratory on the structural type of corrugated-paper-honeycomb cores for use in building panels, as distinguished from use in aircraft. Consideration is given to the resin treatment of the base material and to the fabrication of the core and sandwich panels in the interest of low-cost building material. Strength properties, bowing, thermal properties, durability, and fire resistance of the sandwich panels are discussed. Figure 6 shows a structural sandwich wall panel.

Base Paper

For most experimental work on sandwich panels at the Laboratory, an unsized, neutral kraft paper was selected, because it was strong, potentially available in large quantities, and had favorable indications of permanence. The paper contained no sizing in order to permit better resin penetration and to favor permanence.

A 50-pound (weight per 3,000 square feet) paper was usually employed for cores having cells of A-flute size. Tests were made to explore the possibility of reducing the weight of paper without undue sacrifice of strength in the sandwich panel. The use of lighter-weight papers results not only in an economy of base material but also in a reduction in the amount of saturating resin required to produce a given volume of core. Results showed that sandwich panels with surprisingly high strength properties could be made with paper weighing only 30 pounds per 3,000 square feet, which yielded core of a density of about 2.5 pounds per cubic foot. Thermal insulation data obtained on these core constructions showed that, for a particular core construction, an improvement in thermal values could be achieved by reducing the weight of the paper. The lower limit of paper weight was not determined, as it was felt

that paper of much lower weight than 30 pounds per 3,000 square feet would be difficult to handle in the corrugating and fabricating process.

No information is available on the minimum strength requirements of the base sheet for satisfactory core structures. The relation between ordinary properties of paper and the properties of cores is obscure, and studies should be made to overcome this deficiency. Wet strength can indicate the effectiveness of the resin treatment, ring compression of the sheet may have some significance, and accelerated aging may indicate permanence. Compression, tensile, and shear tests on assembled core are informative but are costly and occur too late to assist paper makers in producing suitable papers.

Until the requirements of paper for use in core can be defined in a more usable form, it will remain difficult to determine the best papers for particular uses. At present, it is certainly safe to assume that any of the ordinary chemical pulps are suitable. For many applications, especially those involving short time expectancy for which maximum permanence is not essential, a high-yield or semichemical pulp may be acceptable or even preferable for structural uses. Reclaimed paper may also provide a suitable fiber for certain panels. Few data are available on the permanence of the high-yield or semichemical pulps. The permanence of the paper may not, however, be critical, since the core material in the sandwich panel is protected from ultraviolet rays, which contribute to the loss of strength of paper upon aging.

Resin-treated Paper

One of the first problems common to any paper core is that of resin treatment of the paper. Although in some cases paper without resin might be acceptable, it is assumed that for general usage only resin-treated papers can be considered. Since panels are likely to be subjected to damp or wet conditions, the presence of resin in the paper is necessary to yield a product that is permanently strong and stiff in the wet condition. Even small amounts of certain resins can be effective in this respect. In terms of tensile strength, it is not difficult to produce a paper that retains over 75 percent of its strength when dry after water soaking that would cause untreated paper to lose almost all of its strength.

The work reported relates to the use of phenol-formaldehyde resins of several types. Two of these are water-soluble and alcohol-soluble types and, although both are suitable, they have inherent differences that need to be considered when they are used with cellulose. With solutions of water-soluble resins, the swelling effect of the water on the fiber permits the resin to penetrate the fiber itself and through a "bulking effect" (10) to maintain the fiber in a swollen state. This also causes a reduction in the equilibrium moisture content of the sheet with water vapor. When alcohol-soluble resin is applied in the absence of a swelling solvent, the effect appears to be chiefly one of coating the fibers. The equilibrium moisture content of such paper, when based on the oven-dry weight of fiber alone, is nearly as high as that of untreated paper (3). Both may have high levels of strength in the wet condition.

Additional evidence that the water-soluble resin penetrates the fiber better than alcohol-soluble resin was indicated by decay tests made on paper treated with both types of resin (8). The results showed that a paper treated with 15 percent of water-soluble resin has considerable resistance to decay fungi, as measured by strength, while the paper containing an equal amount of alcohol-soluble resin lost most of its strength under similar exposure conditions. While the water-soluble phenolic resins are not especially good as fungicides, they can reduce the equilibrium moisture content of the paper and thus discourage the growth of fungi. Inherent brittleness may be a disadvantage of paper impregnated with water-soluble resin.

A resin treatment of 15 percent of water-soluble resin (based on weights of resin and fiber) was found to be adequate for providing paper of good strength when wet, decay resistance, and handling characteristics during corrugation and subsequent fabrication. Resin content in excess of about 15 percent does not seem to produce a gain in strength commensurate with the increased quantity of resin required. The tensile strength of a kraft paper treated with 15 percent of water-soluble phenolic resin may be greater when wet after prolonged soaking in water than the strength of the untreated paper when dry.

Although more than 15 percent of resin may be required for certain uses, it is promising that even a lower resin content will be acceptable for most applications. In one series of tests, paper with as little as 5 percent of water-soluble resin was satisfactory in strength but showed less resistance to decay organisms than a paper with 15 percent of resin. In this case, the addition of 2 percent of pentachlorophenol in the paper overcame the deficiency in decay resistance. The pentachlorophenol was dissolved in a small amount of ethyl alcohol and added to the resin. The concentration of the solution was further reduced by adding a mixture of 50 percent each of water and alcohol. Using this mixture, a kraft paper was treated with 5 percent of a water-soluble phenolic resin and 2 percent of fungicide. The pentachlorophenol did not seem to affect the cure of the resin as indicated by the good strength values of the treated paper and honeycomb structures when wet. Negligible losses in strength resulted from paper impregnated with 5 percent of resin plus 2 percent of pentachlorophenol after 2 months' exposure to two types of wood-destroying fungi. No data are available to indicate the minimum amount of pentachlorophenol required for good decay resistance, but it is likely to be less than 2 percent.

Since resin is the costly item in the honeycomb structures, a series of tests was made to compare the properties of cores containing 5, 10, and 15 percent of water-soluble phenolic resin and 15 percent of alcohol-soluble resin. These cores, of the XN type (fig. 4) with a density of about 2.5 pounds per cubic foot, were bonded to plywood facings, and the panels tested for shear and compressive strength in both the dry and wet condition. When tested dry, panels with 5 percent resin content had a shear stress of 52 pounds per square inch and a compressive strength of 35 pounds per square inch. Increases in saturating resin content of the core resulted in an increase in both strength properties of the panels. Increasing the water-soluble resin content of the core from 5 to 15 percent increased the shear strength of the panels about 40 percent in the dry condition and about 300 percent in the wet

condition. The effect of resin content on compressive strength was not so great as on shear strength. The use of the alcohol-soluble resin as a saturant resulted in slightly higher shear stress developed in bending and compressive strength for dry panels but lower strength for panels tested wet.

Impregnating paper with resin on a separate impregnating machine is likely to be somewhat costly, as it involves a secondary operation. Because the resin content of the paper in the honeycomb core is in the low range, it is reasonably simple to apply resin during the process of paper manufacture as a means of reducing costs if the tonnage required can justify such a process. It is possible to add resin during paper manufacture by:

1. Applying it at the paper-machine size press or similar device.
2. Blending of fiber and resin in water suspension in the beater and retaining this resin in the sheet during paper making.
3. Continuous addition of liquid resin at the machine headbox.

On the experimental paper machine at the Forest Products Laboratory, papers with a wide range of resin content were readily prepared by use of the size-press equipment. These papers were comparable in most respects to matched sheets treated on a separate impregnation machine with the same resin. From numerous experimental trials, it appeared that the size-press treatment was one logical step toward the realization of a lower-cost core material.

In recent years, suitable resins were developed for addition to both the beater and the paper-machine headbox. The retention of early beater-added phenolic resins was very poor, operating difficulties were numerous, and large chemical addition was required to properly precipitate the resin. Several resins exist today that are suitable for this type of addition, and experimental paper-machine runs have been made with promising results. In one series, the addition of 12 or 20 percent of this resin to the pulp slurry tended to free the stock on the machine wire and indicated no special operating difficulties. This is in sharp contrast to the "slowing" of stocks by resin addition in earlier years. The paper after cure of the resin was considerably less brittle than sheets treated with water-soluble phenolic resin on a resin-impregnating machine or size press. An indication of the toughness of the sheet was given by sharply creasing the sheet by hand and then obtaining a tensile strength value across the folded area. The paper retained a surprisingly high percentage of its original strength. Microscopic examination of the papers containing beater-added resin, using an Ultropak microscope equipped with fluorescent lighting, showed only a faint haze of resin, indicating very small particle size and excellent dispersion.

Core Fabrication

Paper for the corrugated type of honeycomb used in this study was corrugated on a 50-inch machine at the Forest Products Laboratory. The A-size fluted

rolls common to the box industry were used. The procedure and weight of paper were varied as needed, depending on the nature of the core desired. Simplest from the standpoint of adaptability to existing equipment is the PNL type of construction (fig. 3). This consists of alternate corrugated and flat sheets and is made by cutting the continuous web of single-faced corrugated paper and bonding these sheets into blocks of considerable thickness, almost exactly as is now done in making blocks for insulation or cushioning in packaging. The only difference, in fact, is in the use of treated instead of untreated paper. In order to make the PNL type of core with A flutes and a density of 2.5 to 3 pounds per cubic foot, it was necessary to use a paper of about 30-pound basis weight (per 3,000 square feet). This core had certain attractive features, such as excellent strength, a slight compressibility in one direction, which aids in fitting pieces of core into a panel of predetermined width, and ease of manufacture.

The XN type of core (fig. 4) was used for most of the data given in this report. To fabricate this type, corrugated sheets were assembled with the principal flute directions of adjacent sheets at right angles and bonded at the crests to form a block of core material. No uncorrugated facing sheet was used for this construction. The base paper, a 50-pound (per 3,000 square feet) kraft paper impregnated with approximately 15 percent of water-soluble phenolic resin, yielded cores with a density of about 2.5 pounds per cubic foot. To assure a good bond between adjacent cross-bonded sheets of corrugated paper in the core, a phenolic adhesive was used in an amount equal to about 10 percent of the weight of the core.

The core was cut and assembled in the sandwich panel with one-half of the flutes perpendicular to the facings. The flutes in the other half of the corrugated sheets were parallel to the facings and contributed very little to the strength of the core, but served rather as spacers for the flutes that carry most of the load. It was demonstrated that the basis weight of the spacer sheets could be reduced from 50 pounds to 30 pounds per 3,000 square feet with very little effect on strength properties of the panel. A further economy in cost could also be realized by reducing the resin content of this lighter paper.

The production of large volumes of this type of core would require certain changes in existing commercial corrugating equipment. Pasting of a flat sheet to the corrugated web is omitted, and more care is needed in handling the web without stretching the corrugations. The crossing of the corrugated sheets would require special but relatively simple equipment.

Either the PNL or the XN type of core can be assembled in the panel so that all the flutes are parallel to the facings of the panel instead of perpendicular. This results in a great improvement in the thermal insulation but a loss in strength. The principal disadvantage of this flatwise construction is that the integrity of the panel itself depends on each glue line between the sheets as well as on the glue line between core and facings.

The PN construction illustrated in figure 5 is similar to the PNL type except that the flat sheet is omitted. The PN type is probably the most difficult of the various corrugated types to fabricate, since it involves placing all corrugated sheets parallel, the crests of each sheet being in direct contact

with the crests of adjacent sheets. To make experimental amounts of this core, segments of ordinary soda straws inserted at the four corners of each sheet were used to achieve good crest-to-crest alinement. This type of core has certain ideal features for studies of materials and design factors. A considerable amount of study was based on this type of core, particularly as related to specialized aircraft parts (6, 9).

Most of the early work in making cores involved the use of costly adhesives to bond paper sheets to each other. In order to better accommodate existing machines and to provide greater economy, a study of the effect of the quality of the bond between sheets of paper on the properties of the sandwich was made. In the assembly of ordinary corrugated board, a nonwater-resistant adhesive is usually employed. It was hypothesized that the bond between individual sheets within the honeycomb core was not critical, since the ends of each flute were bonded to both facings with a high-quality, water-resistant adhesive. The cost of the adhesive and the equipment necessary to use such an adhesive are uneconomical features in the process, unless the high-quality bond is required.

A series of tests was made to compare panels having cores in which individual sheets were bonded with (a) phenolic resin, (b) urea resin, (c) sodium silicate, and (d) no adhesive. Although the assembly of corrugated sheets in a panel without the use of a sheet-to-sheet adhesive is impractical, it was reasoned that the resultant properties would establish the lower limits of strength. The nature of the crest adhesive appeared to have only a slight effect on the shear strength of panels tested in either the dry or wet condition if the web of the corrugation was parallel to the span. Panels with the silicate adhesive had slightly higher strengths when dry and slightly lower strengths when wet than those with the phenolic-resin adhesive. These tests demonstrated that it was desirable to have the web of the corrugation parallel instead of perpendicular to the span to obtain maximum strength, regardless of adhesive used.

Sufficient commercial trials have been made to demonstrate the feasibility of running impregnated papers on corrugating machines, and such papers have been corrugated at ordinary commercial speeds. The ordinary size of flutes used in the box industry produces satisfactory core, but, for economy, it is desirable to use a much lighter paper than the usual corrugating medium for boxes. Another and possibly better approach would be to use larger flutes and heavier papers, resulting in a faster build-up of core of a given density. A few existing machines have larger flute sizes, and any new machine designed expressly for this purpose undoubtedly should use larger flutes.

Panel Manufacture

Facings

Any honeycomb core is satisfactory only in relation to the facings it supports and, conversely, the suitability of any facing may depend on the core. Perhaps one of the best long-term advantages of the sandwich panel is the great latitude it provides in choice of facings and the opportunity to use thin

sheet materials because of the nearly continuous support by the core. The stiffness, stability, and, to a large extent, the strength of the sandwich are determined by the characteristics of the facings. There are a wide variety of sheet materials suitable for facings or skins on honeycomb cores. Some of the different types that have been used include plywood or single veneers overlaid with a resin-treated paper; hardboards; asbestos board; metals, such as aluminum, enameled steel, stainless steel, or magnesium sheet; wallboards; fiber-reinforced plastics or laminates, and veneer bonded to metal.

Plywood is a versatile facing material, and the performance of panels with such facings can now be well predicted. It has good dimensional stability characteristics and strength properties and can be dependably bonded to core with proven adhesives. When exposed to outdoor conditions, some plywoods, such as Douglas-fir, may check considerably, and grain raising becomes apparent. These defects may be eliminated to a large extent by applying a resin-treated paper-overlay sheet to the outer face of the panel, resulting in a smooth surface and uniform base for painting.

Since the facing is securely bonded to the core in the sandwich panel, a two-ply veneer facing, with or without an overlay, can be used as in making flush doors. Although each facing is unbalanced, the panel itself is in balance. Sandwich panels with dissimilar facings may also be suitable for certain uses if the proper unbalance is selected. These might be considered in cases where the exposure conditions on each side are not in balance. Unbalanced panels, however, should be used only with considerable caution. Panels with facings of hardboard or veneer with paper overlays are promising panels from the standpoint of being lightweight and economical. Excess dimensional movement may limit use of this type in some cases.

Cutting of Core

In assembling the core for fabrication of the sandwich panels, the cutting of strips of core material to accurate thickness is essential to avoid difficulty in making or using the panels. Core material may be reduced to the desired thickness by sawing on a circular saw, band saw, vibrating knife, or, in some types, by a guillotine cutter. It may also be made to the desired thickness to avoid cutting. An accurate cut can usually be made with a circular saw, but this requires a rather thin section and therefore more cuts. With the proper blade, speed, and technique, a band saw will reduce the core blocks to proper size within ± 0.015 -inch tolerance, which is probably sufficient for panels of 2 inches or more in thickness. A band saw with five teeth per inch, operating at a blade speed of 3,500 feet per minute, was found to be suitable for most of the test panels. A vibrating-knife type of cutter may be suitable for cutting honeycomb core, because it eliminates the saw-cut losses. For commercial production, it may be desirable to cut the core initially to a broader tolerance and control the thickness accurately with a sander or other machine. It may be sufficient to simply roughen or slit the edges of the core, so that, when pressure is applied to the panel in the press, the effective thickness will be uniform.

Pressing

Satisfactory performance of the sandwich panel depends to a great extent on the bond between the core and facings. The development of sandwich panels was made possible, in fact, by the introduction of high-quality adhesives in recent years.

A study was made of the durability of a number of typical exterior resin adhesives. Paper-honeycomb core made from paper treated with 15 percent of resin was bonded to plywood and tested in tension and shear after exposure to a number of extreme temperature and moisture cycles. The following adhesives produced sufficiently strong bonds between the core and facings to force a high percentage of failure in the core:

- (a) An acid-catalyzed, high-temperature-setting, phenol-resin adhesive.
- (b) An alkaline-catalyzed, intermediate-temperature-setting, phenol-resin adhesive.
- (c) An alkaline-catalyzed, room-temperature-setting resorcinol-resin adhesive.
- (d) An alkaline-catalyzed, high-temperature-setting, phenol-resin adhesive.

The bonding of most of the experimental sandwich panels was done in hot-press equipment. For laboratory work, the short pressing cycle and the long assembly time favored the acid-catalyzed, high-temperature-setting, phenol-resin adhesive. Adhesive was applied to both the core and facings with a rubber roller or an ordinary paint roller at the rate of about 22 grams per square foot of surface, one-half to the core and one-half to the facings. It was also demonstrated that it may not be necessary to apply adhesive to the core in order to produce a satisfactory bond. Core and facings were allowed to stand after spread of adhesive to permit the evaporation of the solvent. Panel components were then assembled and placed in a hot press at a temperature of 230° F. (for the acid-catalyzed phenolic adhesive) to cure the adhesive. Pressures ranging from 15 to 50 pounds per square inch were used, depending on density and type of core construction. Test panels up to 14 feet in length and 6 inches in thickness were made in a 4 by 4-foot laboratory press using step-pressing techniques. Flat sandwich panels were produced with this method.

Special presses are indicated for sandwich-panel manufacture. The pressures required are usually lower than can be obtained in the range of good pressure control on ordinary plywood or plastic presses. Because pressure requirements are low, simple and perhaps less costly presses could be used. Continuous roller presses or bag-molding equipment may also be suitable. Certain special problems arise in the pressing of sandwich panels, but their manufacture is basically not complicated.

Pressing of sandwich panels having dissimilar facings in hot presses has been difficult because of unequal dimensional movement of the facings due to moisture or thermal changes. In such cases, cold-pressing may be necessary. This of course creates its own problems with respect to adhesive limitations, assembly time, water introduced with adhesive, long time under pressure and, in some cases, durability of the bond. Ordinary cold-setting adhesives,

however, are undoubtedly adequate for a host of prospective sandwich-panel applications.

One of the most persistent difficulties in the use of sandwich panels is in the problems caused by the necessity for edges, inserts, and connectors for panels. In some cases, the problem involves tying together thin facing materials without severe stress concentrations and, in other cases, such as furniture, the problem is caused by "show-through" of core or inserts through decorative facings. These problems, probably as much as any other factor, have restricted the development and use of honeycomb core on a larger scale and should be studied from several standpoints. The differential dimensional movement between core and insert materials should be at a minimum, including the rate as well as the degree of movement. Adhesives and moisture introduced by adhesives would be a factor in this study. Examples of materials to consider for edges or inserts would be end-grain wood, plywood on edge, part honeycomb and part wood, metal, dense honeycomb, and mastics or fillers. Another approach would be to study engineering design factors for getting panels into the ultimate product without the use of molded-in inserts; this has certain ideal features from the standpoint of sandwich-panel manufacture, and it simplifies pressing.

Properties of Sandwich Panels

Strength

Strength data were obtained on both large and small sandwich panels comprising paper-honeycomb core with facings of veneer, plywood, hardboard, asbestos board, aluminum, or other materials. These tests included static bending, impact bending, and column tests. The most common test conducted was the static bending test, which consisted of supporting the panels at the ends and applying an increasing load at two quarter-span points. The amount of deflection was recorded at various loads to the design load or until failure occurred. This test not only produced useful information on stresses developed in the facings and on stiffness of the assembly but gave information indicative of the shear strength of the cores and the quality of the bond between core and facings.

In the impact bending test, a 10-inch-diameter sandbag, weighing 60 pounds, was dropped on the center of a large sandwich panel, beginning at a height of 1 foot and increasing by increments of 1 foot to a height of 10 feet or until failure occurred. Panels were supported at each end, and both instantaneous and permanent deflections were measured. The vertical load test was made to determine the ability of a panel to meet certain column structure requirements. The shortening of the panel in the vertical direction and its lateral deflections were measured.

Strength tests conducted on large-size sandwich wall panels, 3 inches thick and having plywood facings, indicated higher shear strengths developed in bending and greater resistance to vertical loads than found in conventional

house construction. These panels withstood maximum loads in bending of at least 12 times the design loads of 20 pounds per square foot sometimes used for house panels.

A considerable amount of design data has been obtained to make it possible to predict the strength of sandwich panels or to design them to meet certain strength requirements. The core of the sandwich may be considered as only a means of separating and stabilizing the facings to produce a member similar to an I-beam. The core simulates the web and the facing the flanges of an I-beam. Since the core in the sandwich is subjected to shear, as is the web of the I-beam, it is essential that the core be sufficiently strong to withstand the shearing stresses imposed. It is assumed, however, that the core itself adds no stiffness to the sandwich construction.

The following formulas are used for predicting the behavior of sandwich constructions subjected to various loads. No consideration is given to concentrations that may occur at joints and fastenings. Each type of fastening will have to be considered individually insofar as its effectiveness in transmitting loads and its strength are concerned.

The constructions are assumed to be well bonded with an adhesive and strong and durable enough to perform adequately for the conditions of use.

The mean stresses in the facings of sandwich construction under flatwise bending loads are given by

$$\sigma_{1,2} = \frac{2M}{f_{1,2}(h+c)b} \quad (1)$$

where $\sigma_{1,2}$ = facing stresses in facings 1 or 2

$f_{1,2}$ = thicknesses of facings 1 or 2

M = moment

h = total sandwich thickness

c = core thickness

b = width of sandwich

The shear stress in the core of sandwich construction under bending loads is given by

$$\tau = \frac{2V}{(h+c)b} \quad (2)$$

where τ = core shear stress

V = shear load

The stiffness of sandwich construction having facings of the same material and equal in thickness is given by

$$D = \frac{E_F(h^3 - c^3)b}{12\lambda} \quad (3)$$

where D = stiffness

E_F = modulus of elasticity of the facings

λ = 0.99 for wood or plywood facings

λ = 0.91 for isotropic facings

The maximum deflection of a sandwich construction having facings of the same material and equal in thickness under a uniformly applied load and simply supported at the ends is given by

$$\Delta = \frac{5Pa^3}{384D} \left[1 + \frac{\pi^2 c^2 E_F}{2\lambda a^2 G_c} \right] \quad (4)$$

where Δ = maximum deflection

P = total load on the sandwich

G_c = shear modulus of the core material

a = span

Note: An approximation of the deflection may be obtained by neglecting the last term in the brackets in formula 4. This term will be less than 10 percent for most constructions on long spans but may become appreciable for short spans.

Strength data for sandwich panels of various thicknesses and comprising different facings are given in table 1. Most of the information on the 3-inch-thick panels was obtained by experimentation, while values for the 1- and 2-inch thicknesses were calculated mathematically with the above formulas. Values in the table show that reducing the thickness of the panel from 3 inches to 1 inch would decrease its stiffness 10 to 15 times and decrease the maximum load that it will support 3 to 4 times. To meet a span-deflection ratio of 270 or more under a uniform load of 20 pounds per square foot, a structural sandwich wall panel on a span of 96 inches would have to be more than 2 inches thick if its facings were of 1/4-inch Douglas-fir plywood. Certain properties of the honeycomb core may be varied considerably with only a mild deviation in stiffness of the resultant sandwich panel.

Dimensional Stability and Bowing of Panels

In a structure such as a sandwich panel in which two facings are bonded to a core to form an integral panel, any dimensional movement of one facing has an effect on the entire panel. A differential movement of facings causes bowing on an unrestrained panel. If dimensional change of both facings is equal, the length and width dimensions of the panel will increase or decrease, but bowing will not result. This is important for many uses. The problem is chiefly related to the facings because the core does not have enough stiffness to cause bowing of the panel or to cause it to remain flat. Laboratory tests have demonstrated that the dimensional stability of a panel is not affected by the type of core. The magnitude of the bowing effect, however, depends on the thickness of core. The use of dissimilar facings is often desirable from an economic standpoint, yet dimensional instability of facings during panel manufacture or exposure may rule out possible benefits, as indicated earlier in this report.

For many applications, such as integral housing panels or what might be described as conventional prefabricated house panels, bowing is almost always a consideration. During exposures in housing when temperature and relative humidity conditions are approximately equal on both sides of the panel, the panel will remain reasonably stable. As cold weather develops, the moisture content on the inner facing of a hygroscopic material decreases and that of the outer facing increases, causing an outward bow. The effects of winter temperatures produce opposite curvatures. During the summertime, the bowing is less pronounced, since the moisture differential is less. This characteristic bowing pattern has been experienced by producers of stressed-skin, plywood prefabricated panels for many years. Although shrinkage and expansion in plywood with moisture changes is slight, the difference is enough to cause a detectable bow. In wood, hardboard, or other hygroscopic materials, warpage can be attributed to both moisture and temperature differences, while in metal-faced sandwich panels, only temperature differences cause dimensional changes, and these changes are due to thermal expansion or contraction.

In conventional construction, it is desirable to install vapor barriers, usually of asphalt-impregnated paper or metal foil, to block the migration of vapor to the cold side of a wall. Various experiments were conducted or proposed to improve vapor resistance of sandwich panels, such as bonding of metal foil; blending aluminum flake with resin bonding adhesives; use of plastic vapor barriers between veneers, overlay papers, and special finishes; and, of course, metal or plastic facings. Because added cost is likely, some of these should not be resorted to unless their need has been demonstrated. Panel edges may also be sealed by various methods if this is indicated. As a generalization, the bowing of sandwich panels is probably neither greater nor less than stressed-skin housing panels having similar facings.

In one series of tests of bowing under laboratory conditions, six sandwich panels, each 3 inches thick, were subjected to severe temperature differences to determine their bowing characteristics. Panels approximately 20 by 72 inches were placed in openings between two rooms, one of which was held at a temperature of -20° F. and the other at +70° F. The edges of the panels were sealed with aluminum foil to prevent the entrance of moisture. The facings

consisted of three-ply, 1/4-inch Douglas-fir plywood with and without paper overlay; two-ply, 1/5-inch plywood with paper overlay; and overlaid, 1/8-inch veneer. One of the plywood-faced panels had two coats of aluminum paint on the warm side only.

All panels deflected slightly toward the warm side immediately after being installed, as the facing on the cold side underwent thermal contraction. As the test progressed, the deflection became less prominent, because the moisture content of the cold side increased. The overlaid, three- and two-ply constructions after 9 weeks' exposure became straight. At the end of the exposure, the overlaid veneer panel showed the greatest deflection, although the overlaid, three-ply panel showed the greatest initial change. After the panels were removed from the wall and exposed to 70° F. on both sides for 3 hours, the panels reversed themselves, bowing toward the cold wall. This was probably caused by the plywood on the cold side undergoing thermal expansion and possibly, in part by the absorption of moisture from the melting of the frost crystals that had formed inside the panels during the exposure. Although these test conditions are not exactly typical of ordinary service conditions, the amount of deflection observed in these panels would not be considered objectionable. Accurate data on the dimensional change of sheet facing materials due to moisture or thermal changes is very important to a study of panel bowing.

It is possible to calculate mathematically the bowing of a sandwich construction if the percent expansion of each facing is known. The maximum deflection due to bowing caused by the expansion of one facing resulting from temperature or moisture differential is given approximately by

$$\Delta = \frac{ka^2}{800h}$$

where k = percent expansion of one facing as compared to the opposite facing

a = length of panel

h = total sandwich thickness

Using this formula, the approximate bowing deflection was calculated for hardboard- and plywood-faced sandwich panels of various thicknesses. This information is given in table 1. The bowing deflection due to moisture or temperature differences is greatly dependent on thickness of the panel. As an example, a 96-inch-long, plywood-faced panel 3 inches thick bows about one-third as much as a similar panel 1 inch thick.

Thermal Conductivity

The basic values determined in establishing the thermal conductivity of a material or combination of materials used in a structure can be defined as follows:

k - thermal conductivity: The time rate of heat flow through a homogeneous material or one of uniform structure under steady state conditions, expressed in British thermal units per hour per square foot per inch of thickness per degree difference in temperature between surface of the material.

U - over-all coefficient of heat transmission, air to air: The time rate of heat flow expressed in British thermal units per hour per square foot per degree difference in temperature.

The term U applies to the combination of materials used in a construction; for example, both facings and core of a sandwich, and includes standard values for f_i and f_o for still air on the warm side and air moving at 15 miles per hour on the cold side.

The usual method of comparing insulating values for wall construction is by comparison of heat transmission coefficients or U values. The U value for a construction is found from the relation

$$U = \frac{1}{\sum \frac{t}{k}}$$

where the values of k are for the several constituents of the wall and t the thickness of these constituents.

To compare insulating characteristics of various core constructions, tests were made on 1-inch-thick specimens using a guarded hot-plate apparatus. The data are summarized in table 2. The conductivity value of the core is affected by: cell size, density, resin content, construction, and type of material. Thermal insulation was significantly affected by the type of construction; values for k varied from as low as 0.30 to as high as 0.65 with variations in core structure. A k value of 0.45 and 0.46 British thermal units per hour per square foot per inch of thickness per °F. was obtained with cross-corrugated (XN) or the parallel-corrugated (PN) structures having flutes perpendicular to facings. By placing these same structures in the test so that flutes were parallel instead of perpendicular to the plates, the value was reduced to 0.30 to 0.31, but these structures have other disadvantages, as mentioned earlier in this report. For any particular core construction, the density of the structure affects the insulation value. As an example, a PNL core having a density of about 5.5 pounds per cubic foot had a k value of about 0.59, while a similarly assembled core, with a density of 3.35 pounds per cubic foot, gave a k value of about 0.47.

An actual U value of 0.150 British thermal units per square foot per hour per °F. was obtained on a 3-inch-thick, large-size panel having the cross-corrugated (XN) type of core and 1/4-inch, three-ply Douglas-fir plywood facings. This panel was exposed in a wall between two rooms, one controlled at 72° F. and 40 percent relative humidity and the other at -20° F. This 0.150 value compares reasonably well with a calculated U value of 0.144 for the same panel. If the thickness of this panel was reduced to 1 inch, the U value could be expected to increase to about 0.42.

An improvement in the insulation value of the sandwich construction can be realized by filling the honeycomb core with insulation or a foamed-in-place resin. A reduction in the k value of a corrugated core from 0.46 to 0.40 British thermal units per hour per square foot per inch of thickness per °F. was obtained when a phenolic resin was foamed into the core. A slightly lower value was obtained through the use of fill insulation. Foaming of resins into honeycomb appears very promising as a means of improving thermal insulation and fire resistance.

Fire Resistance

Sandwich panels were tested for fire resistance by two methods designed for housing materials: (1) Exposing one face of the panel to a standard flame that approximates conditions of fire in a house in which furnishings are being burned; and (2) introducing flame through a hole in the facing, as might occur at openings for electrical conduit or other house equipment.

The first method gives fire-resistance values for sandwich construction that are comparable with those accepted for other types of house construction. The critical factor in this test is the ability of the facings and the bond between the facings and core to resist the high temperature without developing construction failures. Obviously when the facings or bond have failed, the construction is gravely weakened, since the facings are the principal load-carrying elements of the sandwich. At the Laboratory, this test was conducted in a gas-fired furnace according to the exposure conditions specified in American Society for Testing Materials (ASTM) Specification No. E-119-47. The fire resistance of the wood-faced sandwich panels was appreciably higher than hollow panels faced with the same thickness of plywood. When aluminum-faced panels were exposed to the gas, a rather rapid buckling of the facing and failure of the bond usually occurred. In most cases, the cores were badly charred after the test but retained their original form to a considerable extent.

The fire resistance of the sandwich panel can be increased considerably by incorporating in the core foamed resin or an intumescent coating material, such as certain types of sodium silicates. It is conceivable that a material could be developed for deposition in the core that would serve the triple function of bonding the paper sheets, providing foam for fire resistance, and also improving thermal insulation.

By the second method, the likelihood of flame spread in the core was investigated. This was done by cutting a small hole in one facing, holding the panel vertically, and applying a gas flame to a small area for 4 minutes. In panels having flutes perpendicular to the facings, such as in the expanded figure-8 and the corrugated PN and PNL types of core, only slight flame spread occurred. Burning was restricted to the honeycomb material in contact with the flame. When the flame was removed, flaming stopped immediately. Some glow persisted for an additional 1 to 2 minutes. In the case of the cross-corrugated XN type of core in which one-half of the flutes are parallel to the length of the panel, the spread of flame occurred in the vertical direction due to the open channels. This could no doubt be readily improved by placing a

barrier sheet at the top of the panel or at intervals in the panel height, or perhaps by simply turning the length of the core blocks at 90° to the vertical direction.

The resin-treated core in itself is not fire-resistant, but its use between sandwich facings does not seem to be hazardous. It is possible to add fire-resistant chemicals to the paper or to dip or spray the core assembly with such chemicals, but this is believed to be unnecessary when wood-based facings are employed in the panel construction. Such treatments could be effected, if necessary, but might create gluing and moisture-absorption problems, and their effects on long-time aging characteristics of paper are not well understood.

Sandwich-panel Exterior Test Unit

In 1947, an experimental sandwich unit about 12 by 40 feet in size was built on the Laboratory grounds for long-time exposure tests. Incorporated in this unit are various types of sandwich wall, floor, partition, and roof panels. All have paper-honeycomb cores and are faced with veneer, plywood, overlaid plywood, hardboard, asbestos board, or aluminum for comparative purposes. The unit on the inside is equipped with heating coils and is controlled during the winter at a temperature of 72° F. and a relative humidity of 40 per cent. The outside of the unit is exposed to the variable outdoor temperatures of the Madison, Wis., area.

Before the wood-faced and aluminum-faced panels were installed in the test unit, they were tested to determine their deflection and span-deflection ratios at design loads. The 3-inch-thick, wood-faced wall panels met the requirement that the span-deflection ratio be not less than 270 under a design load of 20 pounds per square foot. Floor panels of 6-inch thickness with facings of 3/8-inch, five-ply Douglas-fir plywood had a span-deflection ratio of about 800 under a load of 40 pounds per square foot (11).

After 16 months' exposure, four wall panels were removed from the experimental unit for test. Two panels had facings of 1/4-inch Douglas-fir plywood, and two had facings of 1/8-inch Douglas-fir veneer overlaid with paper. Cores were of the cross-corrugated XM type. On removal, the panels showed no visible signs of deterioration in either the core or the facings. The stiffness of the exposed panels was equal to or slightly greater than their stiffness prior to installation. This increase in stiffness may possibly be due to the further cure of the resin upon aging. Maximum loads obtained on these panels varied from 13 to 20 times the design load of 20 pounds per square foot.

To obtain additional information on the effect of continuous weathering on appearance and strength, sandwich panels having 1-inch-thick, paper-honeycomb core and various wood facings with and without paper overlays were subjected to the following conditions in the Laboratory:

1. Immersed in water at 122° F. for 1 hour.
2. Sprayed with wet steam at 194° to 200° F. for 3 hours.
3. Stored at 10° F. for 20 hours.
4. Heated in dry air at 212° F. for 3 hours.

5. Sprayed with wet steam at 194° to 200° F. for 3 hours.
6. Heated in dry air at 212° F. for 18 hours.

This sequence of exposures was continued through six cycles, after which appearance of the specimens was noted, and bending tests were made to determine any change in strength properties. Results of these tests were compared with those of tests made on control specimens not subjected to the aging tests. The reduction in shear stress developed in the cores of the aged specimens was about 20 to 30 percent as compared with that of the control specimens. Reduction in stiffness was about 20 percent as obtained from a comparison of load-deflection ratios. The sandwich specimens were exceptionally straight, and no visual defects were apparent in the core. Although accelerated aging tests are never completely satisfactory, the performance of such specimens plus the observations made on the actual exposure unit indicate that good performance could be expected.

One of the reasons for building the test unit was to obtain measurements of the actual bowing under outdoor conditions. Some data were obtained during the first year of exposure of these panels. Shortly after the unit was constructed in June 1947, deflection data showed a tendency of the panels with wood facings to bow slightly inward. In November when the heating system was turned on, the wood panels reversed their movement and bowed outward. The outward bowing was due to the lower outside temperature, which caused an increase in moisture content of the outer facing, and the shrinkage of the inner facings due to the heat. The bowing increased progressively in the wood-faced panels as the average outdoor temperature decreased and continued until late in March when the outdoor temperature began to rise again. The maximum bowing recorded in plywood-faced panels was about one-fourth inch. Aluminum-faced panels, not being affected by moisture, bowed toward the inside as the temperature of the outside dropped. On a hot day with a high surface temperature on the outside, an outward bow could be noted. Results of the first year indicated that bowing of sandwich panels with facings of three-ply plywood is consistent with that of panels with three-ply stressed facings. Whether the inner surface was untreated, had aluminum paint, or had an overlay appeared to be unimportant in panels with three-ply facings.

As the development of the sandwich structural panel grows, the need for more data on the behavior of such panels under ordinary exposure conditions will increase. It is hoped that this test unit will be helpful in resolving some of the problems regarding large-scale use of sandwich panels. Although there are many other uses for sandwich panels, the evaluation of these panels under housing conditions provides information that applies to most other products in which use of sandwich panels might be considered.

No attempt is made in this report to detail actual or proposed uses for sandwich panels, but these include partitions, doors, spandrell panels, and other constructions in houses, trailers, shelter buildings, warehouses, and farm buildings, lightweight shipping containers, and furniture. Because of the inherent structural strength of these panels, the greatest total benefit can probably be realized by using them to carry the principal loads in a construction, not just to provide coverage. The general trend toward the use of sheet materials, both on the inner and outer surfaces of buildings, also points to long-term importance of sandwich panels as building materials.

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Table 1.--Stiffness and strength of structural sandwich panels on a 96-inch span¹

Facings	: Panel : : thick- : ness :	Center : deflection ² : In.	: Span- deflection : ratio ² :	: Maximum : uniform : load :	: Approximate : bowing : deflection ³ :
		In.		Lb. per sq. ft.	In.
1/4-inch Douglas-fir plywood	: 3 : : 2 : : 1 :	: 0.184 : : .453 : : 2.320 :	: 521 : : 212 : : 40 :	: 300 : : 192 : : 82 :	: 0.38 : : .58 : : 1.15 :
Two 1/10-inch Douglas-fir veneers with paper overlay	: 3 : : 2 : : 1 :	: .207 : : .483 : : 2.140 :	: 464 : : 199 : : 45 :	: 268 : : 175 : : 85 :	: : : : : :
One 1/8-inch Douglas-fir veneer with paper overlay on each side	: 3 : : 2 : : 1 :	: .169 : : .396 : : 1.810 :	: 568 : : 242 : : 53 :	: 332 : : 216 : : 101 :	: : : : : :
1/4-inch tempered hardboard	: 3 : : 2 : : 1 :	: .202 : : .498 : : 2.630 :	: 475 : : 193 : : 36 :	: 344 : : 218 : : 94 :	: 1.00 : : 1.50 : : 3.00 :
1/8-inch tempered hardboard	: 3 : : 2 : : 1 :	: .313 : : .735 : : 3.350 :	: 306 : : 130 : : 29 :	: 269 : : 176 : : 82 :	: : : : : :

¹All cores of the cross-corrugated KN type were made from 50-pound paper treated with 15 percent of resin. The core density was 2.5 pounds per cubic foot.

²Deflection under a uniform load of 20 pounds per square foot on a span of 96 inches.

³Midspan deflection computed from the differential expansion of the two facings obtained by exposure of one facing to a relative humidity of 97 percent, the other to a relative humidity of 30 percent for 30 days.

Table 2.--Effect of core construction, density, and filler on thermal conductivity of core made from resin-treated paper

Core construction :	Filler in core :	Density :	k :	$\frac{1}{k}$:
		<u>Lb. per cu. ft.</u>	<u>B.t.u. per hr. per</u>	
			<u>sq. ft. per inch</u>	
			<u>per ° F.</u>	
XV :	None :	2.75 :	0.45 :	2.22 :
PN :	.....do..... :	2.94 :	.46 :	2.17 :
PI :	.....do..... :	5.47 :	.58 :	1.73 :
PNL :	.....do..... :	3.35 :	.47 :	2.13 :
PNL :	.....do..... :	5.50 :	.59 :	1.69 :
Figure 8 :	.....do..... :	2.89 :	.53 :	1.89 :
PN :	Foamed resin :	5.36 :	.40 :	2.50 :
Figure C :	.....do..... :	1.88 :	.31 :	3.23 :
PN :	Fill insulation :	4.72 :	.37 :	2.70 :

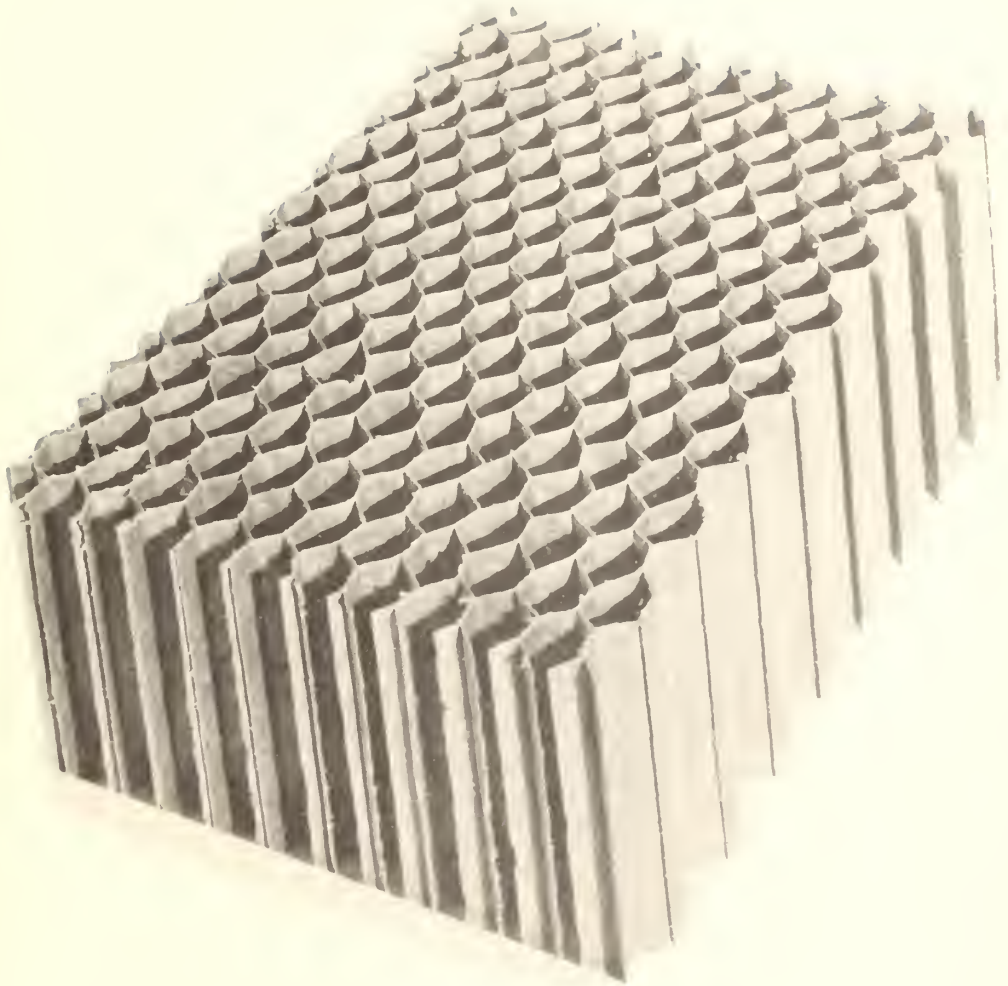


Figure 1.--Expanded type of core consisting of sheets of paper interspaced with parallel strips of adhesive and expanded to form hexagonal cell sections.

Z. N. 87220 F

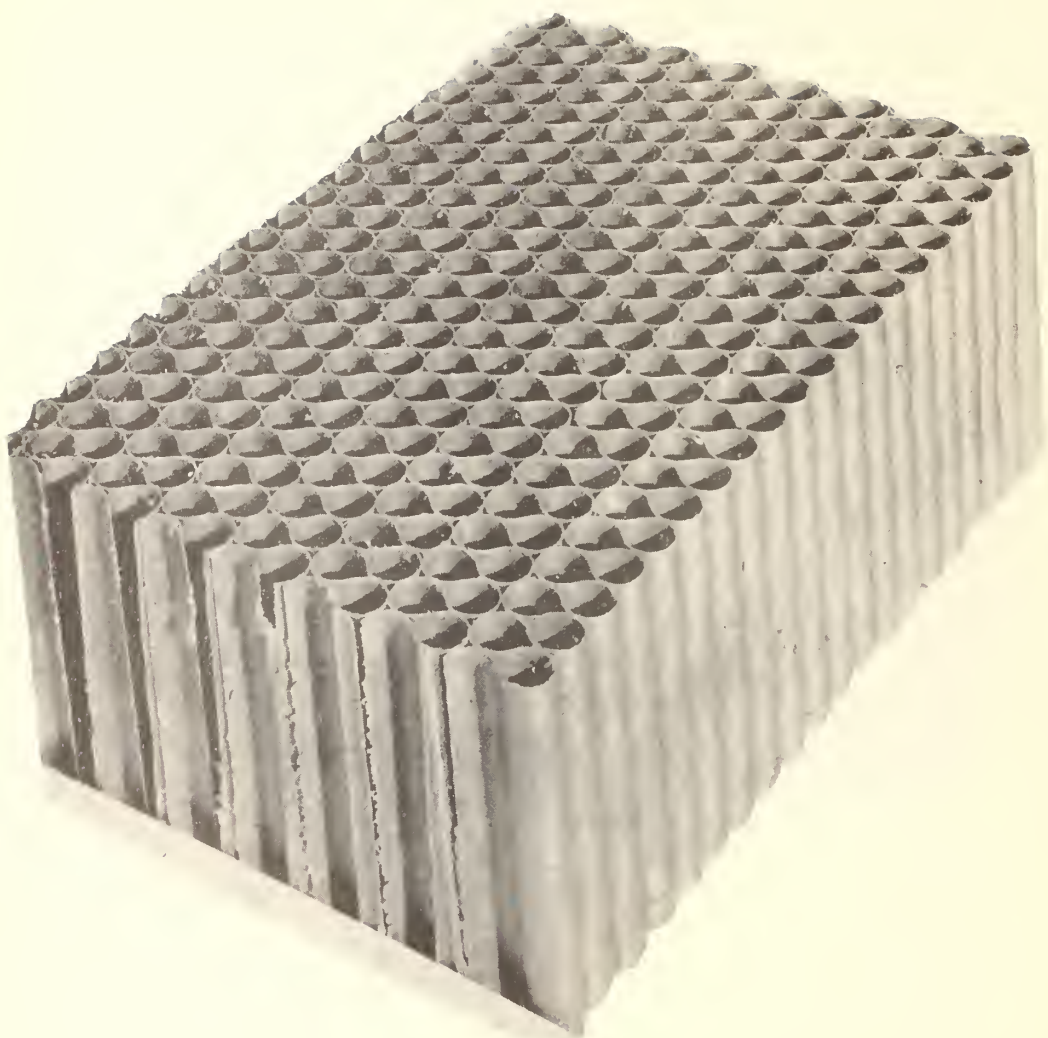


Figure 2.--Looped or figure-8 type of core consisting of sheets of **paper** looped and bonded to form circular cells.

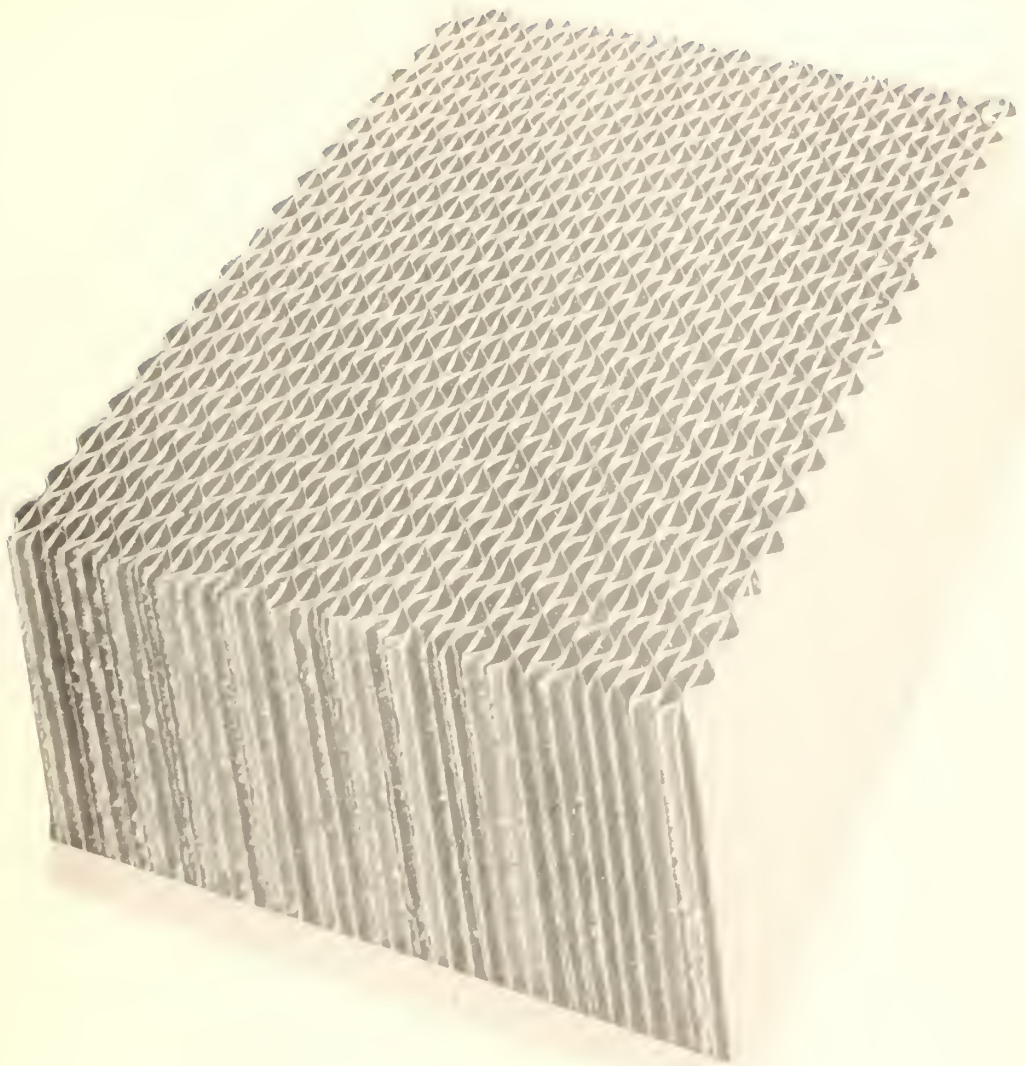


Figure 3.--Corrugated type of core designated as PNL. It consists of corrugated sheets of paper assembled parallel to each other and separated by a single treated, and uncorrugated sheet.

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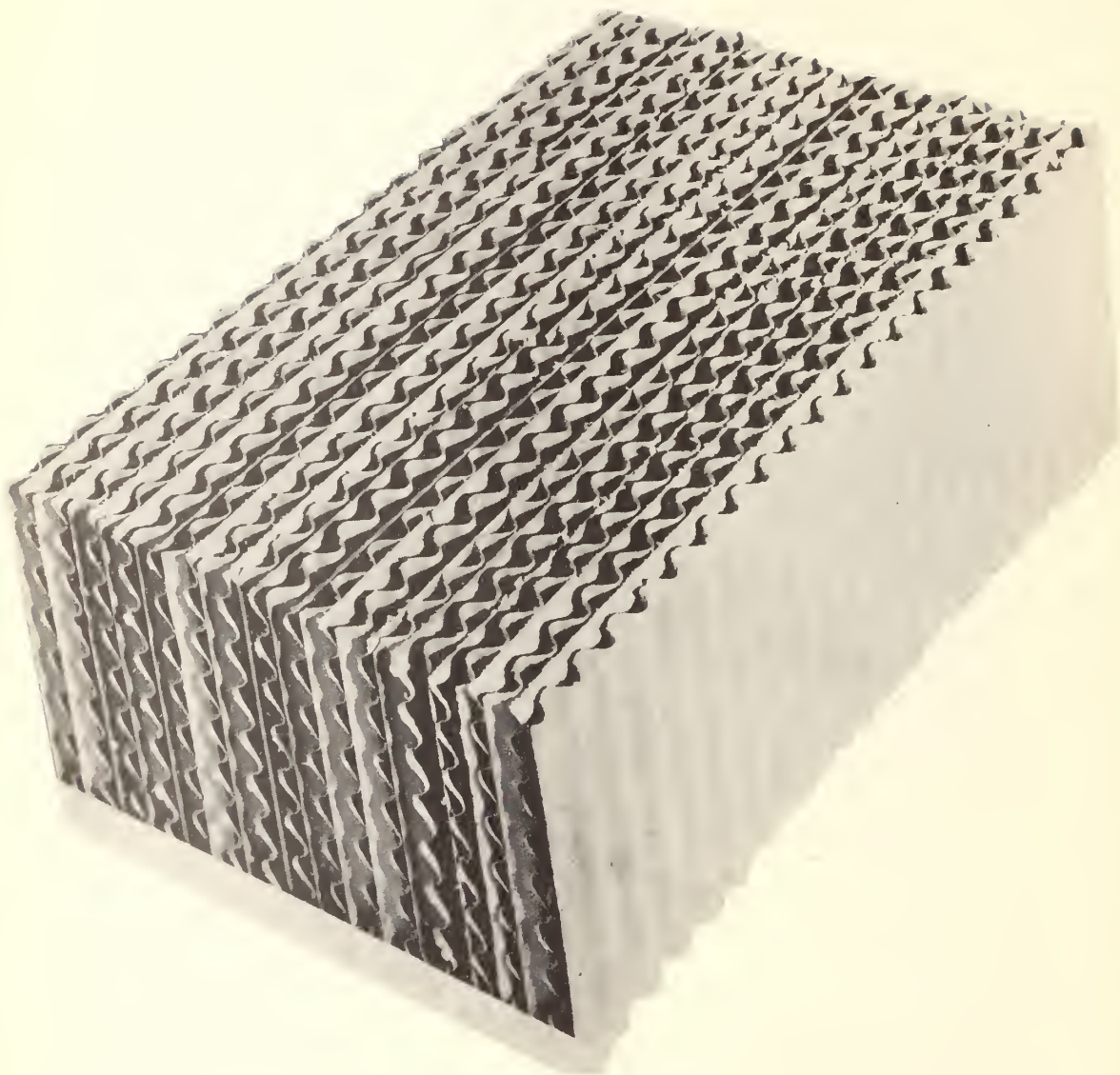


Figure 4.--Corrugated type of core designated as XN. It consists of corrugated sheets assembled with principal flute directions of adjacent sheets at right angles.

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Figure 5.--Corrugated type of core designated as PN. It consists of corrugated sheets assembled parallel to each other and bonded at the crests.

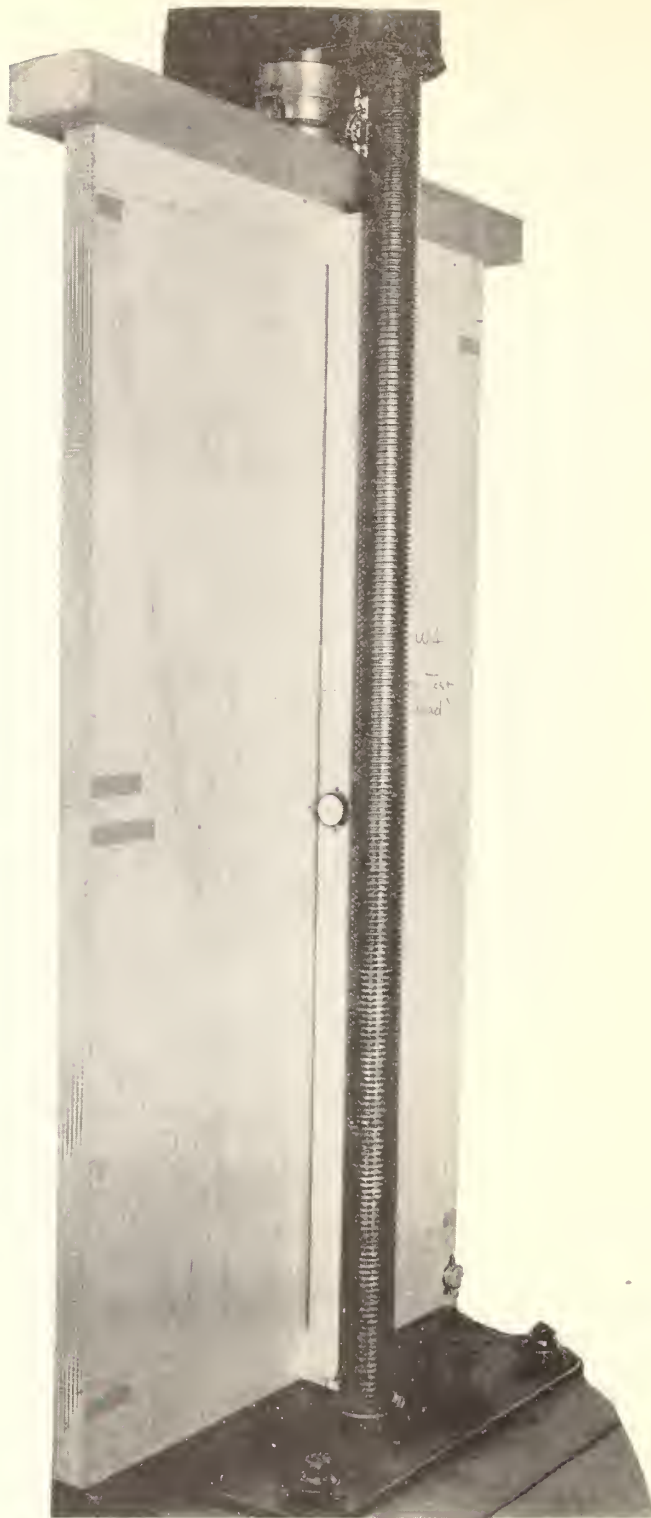


Figure 6.--Structural sandwich wall panel tested under vertical load.

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